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Final Report for Period: 10/1997 - 11/2002

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Principal Investigator: Germanovich, Leonid N.

Award ID: 9896021

Organization: GA Tech Res Corp - GIT

Title:

Toward an Integrated Mathematical Model of Seafloor Hydro- thermal Systems Involving Fracture Mechanics,Chemistry, and the Evolution of Crustal Permeability

Project Participants

Senior Personnel

Name: Germanovich, Leonid

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Roegiers, Jean-Claude

Worked for more than 160 Hours: No

Contribution to Project:

Jean-Claude Roegiers is not a Co-PI on this project. He is at another school (The University of Oklahoma) and his name is probably kept because this award was transfered from Oklahoma to Georgia Tech. Transfer documentation does not show Jean-Claude Roegiers and he has no involment in this project.

Post-doc

Graduate Student

Name: Astakhov, Dmitriy

Worked for more than 160 Hours: No

Contribution to Project:

Name: Sim, Young-Jong

Worked for more than 160 Hours: Yes

Contribution to Project:

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

This project represents a close collaborative effort with Dr. Robert Lowell in the School of Earth and Atmospheric Sciences at Georgia Tech. He is a PI of project OCE-9529954 entitled 'Towards an integrated mathematical model of seafloor hydrothermal systems: emphasis on the magma-hydrothermal interface, upflow zones and temporal variability'. This project has exactly the same title and is run in the close cooperation with Dr. Lowell.

Activities and Findings

Research and Education Activities:

Research Activity

This was a collaborative project between the PIs Dr. Robert Lowell and Dr. Leonid Germanovich at the Georgia Institute of Technology. The goal of this research has been to develop robust mathematical models of seafloor hydrothermal systems that will eventually lead to integrated models that can describe a wide variety of phenomena. The models are closely linked to observational data.

During this grant we worked on a number of separate but interrelated projects. Most of these involved our direct collaboration. In some cases, however, the PIs worked with his students or other researchers independently. The individual research projects are listed below and further details are given in the section on Findings:

(1) Event plumes
(2) Role of thermoelastic stresses on behavior of seafloor hydrothermal systems
(3) Permeability evolution in hydrothermal systems
(4) Fluid flow in hydrothermal systems
(5) Anhydrite precipitation in hydrothermal systems

The results of this work have been reported at a number of scientific meetings. The specific citations are given below.

Germanovich, L. N., R. P. Lowell, L. M Ring, and D. K. Astakhov, Thermoelastic mechanisms of temporal variability in hydrothermal venting, AGU, Eos, 77, (Fall Meeting, Suppl.), F727, 1996.

Germanovich, L. N., D. K. Astakhov, and R. P. Lowell, Formation of event plumes at ocean ridges resulting from dike injection, AGU, Eos, 78, (Fall Meeting Suppl.), F765, 1997.

Astakhov, D. K., L. N. Germanovich, and R. P. Lowell, Effect of stress dependent permeability on seafloor hydrothermal circulation, AGU, Eos, 79, (Fall Meeting Suppl.), F45, 1998.

Germanovich, L. N. and D. K. Astakhov, Pressure dependent permeability in jointed rock, AGU, Eos, 79, (Fall Meeting Suppl.), T72G-09, 1998.

Germanovich, L. N., R. P. Lowell, and D. K. Astakhov, Bifurcation in seafloor hydrothermal flow, AGU, Eos, 80, (Fall Meeting Suppl.), F931, 1999.

Lowell, R. P., and L. N. Germanovich, Single-pass models for seafloor hydrothermal systems, AGU, Eos, 81, (Fall Meeting Suppl.), F458, 2000.

Astakhov, D. K., and Germanovich, L. N., 2000, Fracture closure in extension and stress dependent permeability, Proceedings of the 4th North American Rock Mechanics Symposium: NARMS 2000, J. Girard et al. (eds.), Balkema, Rotterdam and Brookfield, pp. 841-848

Lowell, R. P., and L. N. Germanovich, Single-pass models for seafloor hydrothermal systems, Earth System Processes Meeting, Edinburgh, Scotland, June 24-28, 2001.

Lowell, R. P., P. A. Rona, and L. N. Germanovich, Mathematical models of seafloor hydrothermal systems driven by the serpentinization of peridotite, AGU, Eos, 82, (Fall Meeting Suppl.), F1101, 2001.

Germanovich, L. N., P. E. Dijk, and R. P. Lowell, Visualization of Transport Phenomena and Fracture Evolution in Fractured Media, AGU, Eos, 82, (Fall Meeting Suppl.), H51D-0356, 2001.

Educational Activity

This grant supported graduate students and undergraduate students. The results of this research are incorporated into both undergraduate and graduate level courses that we teach. In particular, EAS/CEE 6751 Physical Properties and Rheology of Rocks), which is co-taught by the PIs, and EAS 4515/6128 Fluids in Earth's Crust, which is required for the geohydrology certificate in CEE, are commonly taken by students in both

CE and EAS. We also plan to make our mathematical and numerical models available to the broader community both as educational and as research tools at our hydrothermal website (http://epr10.eas.gatech.edu). We are currently developing a web-based version of the single pass models for use as an educational tool. This will be a simplified version of the SP code that will be useful non-specialists and as a teaching aid for courses in geohydrology and marine geophysics. Users we be able to use this application to conduct quick parametric analysis and obtain basic results on the temperature and heat output of high-temperature ridge crest hydrothermal systems as functions of crustal permeability, magma-hydrothermal boundary layer thickness, recharge and discharge areas, etc. With further development we will enable the application to provide useful results concerning: (a) the formation of sulfide deposits, (b) rates of permeability sealing by quartz and anhydrite, (c) estimates of the ratio of reservoir heat to dike heat in an event plume, and (d) semi-quantitative understanding of system bifurcations.

Findings:

Findings

1. Event plumes [Germanovich et al., 2000]

We address the question of formation of event plumes following dike emplacement in a hydrothermal upflow zone at a mid-ocean ridge. We assume a preexisting low- to moderate-temperature single-pass hydrothermal system and suggest that dike emplacement provides a damaged zone of high permeability along its margins as well as the heat required to drive the event plume. We also consider the role of thermoelastic stresses in limiting the heat output of the event plume. Our calculations show that event plumes can result from dike emplacement into a preexisting, moderate-temperature hydrothermal system, provided the local permeability generated by the dike is ~ 10-8 - 10-10 m2. These values are consistent with our limited field observations from the Susanville ophiolite, suggesting that the permeability near dike margins attributed to dike emplacement results mainly from open fractures mostly aligned parallel to the margins of dike. We estimate the porosity in the damaged zone to be of the order 0.1-1%. If the high-permeability zone has relatively low porosity (~ 0.1%), thermoelastic stresses close the fractures sufficiently to reduce the heat output, giving rise to a weak event plume (~ 1014 J). If the porosity is higher (? 1%), however, thermoelastic stresses become unimportant, and a similar dike can generate an event plume of ~ 1017 J. Following event plume emission, the circulation decays rapidly to its original temperature; however, the heat output from the chronic plume is greater because of the increased permeability resulting from dike emplacement. The decay of heat output to preevent plume levels requires that the newly created permeability be sealed, perhaps as a result of chemical precipitation in the cracks.

2. Thermoelastic Stresses [Germanovich et al., 2001]

We investigate the effects of temperature-dependent permeability in a hydrothermal upflow zone on the evolution of a seafloor hydrothermal system. Our mathematical modeling of a seafloor hydrothermal system with temperature-dependent permeability suggests that the system can be in one of two stable regimes of heat transfer. In one regime, heat conduction and thermoelastic effects do not play a significant role because the rock thermal expansion coefficient is too low or the rock porosity is too high. In the other regime, thermoelastic stresses reduce the permeability by orders of magnitude, and some fraction of the heat is transferred by conduction. In both regimes, essentially the same amount of heat is transported by the upflow but with different flow parameters. When thermoelastic stresses reduce the permeability, discharge occurs at relatively high temperature and low flow velocity, whereas when thermoelastic stresses have little effect on the permeability, discharge occurs at much lower temperature and higher flow velocity. The existence of two stable states of the hydrothermal system results from the nonlinearity of the dependency of permeability upon temperature and from specifying the heat flux entering the system. Consequently, a hydrothermal system can be on one or another solution branch, depending on small variations in system parameters, its history, and boundary conditions. At the top of the hydrothermal system the temperature difference between the branches can reach several hundred degrees. Relatively small changes in basal heat flux or rock permeability in the upflow zone can rather quickly switch the system from one stable branch to another. Such permeability changes may result from magmatic events, earthquakes, or chemical dissolution or precipitation. The calculations show that it is easier to drive the system from the high-temperature branch to the low-temperature one than vice versa.

3. Permeability Evolution [Germanovich and Astakhov, 2002, in press]

It is well known that the permeability of a set of fractures can significantly vary in response to in-situ stress conditions and pressure of the flowing fluid. Frequently, fracture sets are closely spaced and although their mechanical interaction could significantly affect their aperture, the interaction is usually ignored in permeability evaluation. It is rather obvious that this approach corresponds to the upper limit for rock permeability. By taking into account the interaction between the fractures, we show that modeling a fracture set by an infinite array provides the lower limit. Furthermore, because the internal pressure can, in fact, close the pressurized fractures while two edge fractures in the set remain widely open (since they are not suppressed from one side by the adjacent fractures), unless the number of fractures in the set is exceedingly large (typically, > 103), the fluid flow through the fracture set becomes highly heterogeneous, focusing in the edge fractures. As the fracture spacing lessens, the permeability decrease, due to the closure (suppression) of internal fractures, is compensated by the permeability increase because of the higher fracture density. As a rsult, the permeability dependence on the fracture spacing is not monotonic, but has a maximum and a minimum. Yet, stress-dependent permeability, computed more accurately when accounting for fracture interaction, is always lower (and often by orders of magnitude) than that based on the assumption of non-interacting fractures.

4. Fluid Flow [Germanovich and Astakhov, 2002, in press]

It is well known that in many cases rock permeability depends upon in-situ stress conditions and on the pressure of the flowing fluid. Parallel and quasi-parallel fractures represent one of the most often observed permeability structures. An important example is given by margin fractures in sheeted dikes at the base of mid-oceanic ridge hydrothermal systems. Frequently, fracture sets are closely spaced and although their mechanical interaction could significantly affect their aperture, the interaction is usually ignored in permeability evaluation. In this paper, based on accurate computations of the interaction between the parallel fractures and conducted physical experiments, we suggest that the internal pressure can, in fact, close the pressurized joints. In general, there is a critical spacing between the parallel fractures below which their surfaces start contacting under the extensional load. However, two edge fractures (end members) in the set remain widely open because they are not suppressed from one side. These effects dramatically change rock permeability and the fluid flow pattern.

5. Anhydrite Precipitation [Lowel, Yao, and Germanovich, 2002, submitted]

The mechanisms that control the style of high-temperature hydrothermal discharge at ocean ridge crests are not well understood. Sites of vigorous high-temperature focused venting are often accompanied by nearby regions of low temperature diffuse flow. Moreover, at some sites high-temperature fluids are not focused at all and emerge as low temperature diffuse flow as a result of conductive cooling and/or mixing with cooler seawater; whereas at others discharge has evolved from low temperature diffuse flow to high-temperature focused flow over a number of years. To better understand the mechanisms that control these discharge styles we construct a two-branch single-pass hydrothermal circulation model to investigate the role anhydrite precipitation upon mixing between deep-seated, high-temperature, sulfate-free upflow and cooler, sulfate-rich seawater circulating through permeable pillow basalts. We also estimate the width of the impermeable anhydrite barrier between focused and diffuse discharge. The model results suggest that focusing can occur in a matter of years provided the permeability in the deep part of the discharge zone is greater than or equal to that of the mixing zone and the permeability of the mixing zone is initially high (~ 10-11 -10-12 m^2). Absence of focused discharge suggests one of these conditions is violated. The width of the impermeable barrier resulting from the precipitation of anhydrite ranges between 1 and 100 m, thus permitting diffuse flow to occur in close proximity to focused discharge.

Training and Development:

Grant OCE-9896021 has been used to support Dr. Dmitriy Astakhov who completed his Ph.D. thesis and graduated in 2000 as well as Mr. Young Jong Sim who is comleting his Ph.D. work. Project results are used in graduate courses 'Physical properties and rheology of rocks,' 'Fractures and flow in geomaterials,' and 'Rock Mechanics'

Outreach Activities:

Project results are used in graduate courses 'Physical properties and rheology of rocks,' 'Fractures and flow in geomaterials,' and 'Rock Mechanics.' These courses were taught to primarily civil and environmental engineering students who are usually not aware of marine geophysics research. Part of the material was presented in the engineering context highlighting internal connection between apparently different topics.

Journal Publications

Germanovich, L. N., R. P. Lowell, and D. K. Astakhov, "Temperature-dependent permeability and bifurcations in hydrothermal flow", J. Geophys. Res., Solid Earth, p. 473, vol. 106, (2001). Published

Astakhov, D. K. and Germanovich, L. N., "Fracture closure in extension and mechanical interaction of parallel joints", J. Geophys. Res., Solid Earth, p. , vol. , ( ). Accepted

Lowell R. P., Yao, Y. F., and L. N. Germanovich,, "Anhydrite precipitation and the relationship between focused and diffuse flow in seafloor hydrothermal systems", J. Geophys. Res., Solid Earth
, p. , vol. , ( ). Submitted

Germanovich, L.N., R.P. Lowell, and D.K. Astakhov, "Stress dependent permeability and the formation of seafloor event plumes", J. Geophys. Res., Solid Earth, p. 8341, vol. 105, (2000). Published

Germanovich, L. N., and Astakhov, D. K., "Stress dependent permeability and fluid flow through parallel joints", Journal of Geophysical Research, Solid Earth, p. , vol. , ( ). Accepted

Lowell, R. P., and Germanovich, L. N., "Evolution of a brine layer at the base of a ridge-crest hydrothermal system", Journal of Geophysical Research, p. 10,245, vol. 102, (1997). Published

Books or Other One-time Publications

Astakhov, D. K., and Germanovich, L. N., "Fracture closure in extension and stress dependent permeability", (2000). Refereed Conference proceeding, Published
Editor(s): J. Girard et al.
Collection: Proceedings of the 4th North American Rock Mechanics Symposium: NARMS 2000
Bibliography: Balkema, Rotterdam and Brookfield, pp. 841-848.

Lowell, R. P. and L. N. Germanovich, " Hydrothermal Processes at Mid-Ocean Ridges: Results from Scaling Analysis and Single-Pass Models", ( ). Book, Submitted
Collection: Inter Ridge Theoretical Institute Volume, Pavia, Italy
Bibliography: AGU Monograph

Astakhov D.K., "Permeability evolution as a result of fluid-rock interaction", (2000). Thesis, Published
Bibliography: Ph.D. Thesis, Georgia Institute of Technology, Atlanta

Web/Internet Site

URL(s):
http://epr10.eas.gatech.edu
Description:

Other Specific Products

Contributions

Contributions within Discipline:
As a result of this grant, a series of robust, understandable, mathematical models constrained by existing observational data that are broadly accessible to the scientific community has been developed. These models highlight the fundamental connection between hydrothermal circulation, heat flow, and geochemical processes.

Contributions to Other Disciplines:
The developed models of stress- and temperature-dependent permeability and fluid flow in fractured rocks are important for hydrogeology, hydrology, rock mechanics, petroleum engineering.

Contributions to Human Resource Development:
A graduate student, Dmitriy Astakhov, graduated with Ph.D. degree with the support from this project. In addition, he served as Graduate Research Assistant for course CEE 6451 Rock Mechanics. This course incorporated results from this project.

Contributions to Resources for Research and Education:
We are currently developing a web-based version of the single pass models for use as an educational tool. This will a simplified code that will be useful non-specialists and as a teaching aid for courses in geohydrology and marine geophysics. Users we be able to use this application to conduct quick parametric analysis and obtain basic results on the temperature and heat output of high-temperature ridge crest hydrothermal systems as functions of crustal permeability, magma-hydrothermal boundary layer thickness, recharge and discharge areas, etc.

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners
Any Product

Contributions: To Any Beyond Science and Engineering